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ABSTRACT

Late Palaeozoic glaciation is the longest of the Phanerozoic era. It is recorded in numerous Gondwanian basins, some having a high petroleum potential like the Chaco Basin. In this basin, the quality of the available seismic, well and outcrop data permits to characterise the Late Palaeozoic glacial record. Palaeovalleys >500 m deep and ~7 km wide have here been analysed. Focusing on the glaciogenic Carboniferous deposits, the seismic data with well-ties and their outcrop analogues provide new sedimentological insights. The palaeovalley infill is imaged as a chaotic seismic facies overlain by an aggrading-prograding prism, interpreted as tillites covered by a fluvio-deltaic system respectively. Tillites form both under the ice and during rapid ice recession whereas fluvio-deltaic systems can only originate from a stable ice margin and last until the ice sheets withdraw inland. These two depositional

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modes are repeated several times generating the progressive burial of the Carboniferous palaeovalleys. This succession of erosions and fills records major glacial stages containing a series of glacial and interglacial phases from the Late Devonian to the Early Permian. Depicting the Late Palaeozoic glacial history of the Chaco Basin seems crucial for the localisation of potential good reservoirs.

INTRODUCTION

The Late Palaeozoic Ice Age, developing from the Late Devonian (c. 390 Ma) to the Mid Permian (c. 270 Ma (Hambrey and Harland, 1981)), generated the largest cyclic sedimentary deposits in Phanerozoic history (Caputo *et al.*, 2008). It affected a large part of the supercontinent Gondwana, leaving evidences of ice activity in Australia, Antarctica, Arabic Peninsula, India, South Africa and South America (Crowell and Frakes., 1975). The ice masses first developed in South America and South Africa during the Early Carboniferous. During the Late Carboniferous, the ice sheets were situated in India, Australia and Antarctica. The peak of the ice age occurred in Antarctica and Australia during the Permian (Crowell and Frakes., 1975; Caputo and Crowell, 1985). The Late Palaeozoic glaciation coincides with the greatest episode of coal accumulation on Earth and consequent atmospheric CO_2 sequestration.

In South America, Late Palaeozoic glaciogenic rocks were first observed in the early 19th Century (Wegener, 1915; Du Toit, 1937). Ice ages were usually examined by field studies, based on the occurrence of diamictites containing striated clasts attributed to ice-rafted debris or on glacial striated pavements recognition. Glacial valleys later became the main evidence of direct ice activity and, consequently, have been searched for within glaciogenic successions. Field mapping of the glacial surfaces led to the recognition of different types of glacial valleys associated with continental ice-sheets: (1) tunnel valleys, related to the incision of overpressurised meltwater; (2) cross-shelf troughs, related to ice-stream activity and abrasion processes; and (3) fjords which result from melt-water and abrasion erosion processes. Despite the development of subsurface seismic studies, palaeofjord incisions have rarely been described for ancient ice ages.

This paper aims at describing the seismic signature of the Late Palaeozoic succession in the Bolivian Chaco Basin which contains some very large-scale glacial incisions. The seismic stratigraphy provides new insights into the tectonics, the palaeoenvironment and the palaeoglaciology of the Chaco Basin.

REGIONAL SETTING

The Bolivian Chaco Basin is part of foreland basins associated with the Andean orogenic system and is identified as a backarc flexural intracratonic basin of Cenozoic age (Sempere *et al.*, 1990; Decelles and Horton, 2003). The basin is bounded to the north and north-east by the Brazilian craton, and to the west by the subandean fold and thrust belt zone which constitutes the eastern border of the Andes (Fig. 1). Since the late Oligocene, the deformation propagated toward the E and NE, uplifting the eastern part of the Andean depocentre (Sempere, 1995). Consequently, the Phanerozoic strata are well exposed in the Bolivian Andes. A Precambrian-Tertiary clastic stratigraphic section is exposed in the Andean and the sub-Andean fold belts of southern Bolivia (Fig. 2), where shallow marine Ordovician-Devonian clastics are conformably overlain by a Carboniferous to Upper Permian sequence. The Palaeozoic succession is unconformably overlain by Cretaceous fluvial sediments and Cenozoic progradational foreland basin deposits (Dunn *et al.*, 1995).

In the Chaco Basin, the Izozog High (Fig. 3) is the result of an uplift that occured prior to the Cretaceous Period (Gohrbandt, 1992; Uba *et al.*, 2006). Paleozoic units are tilted toward the W and NW and eroded at the top of the High (Fig. 4). This erosion is in part responsible for the variation in the thickness of the Paleozoic units (Fig. 5). The Carboniferous section is characterized by a continuous succession of well-developed massive sandstone units (Tupambi, Chorro, and Escarpment Fms.; Fig. 2) that alternate with thinner, muddy diamictite intervals (Itacuami, Tarija, Taiguati, and San Telmo Fms.; Fig. 2). This alternating succession is interpreted to result from episodic tectonic or climatic events (Helwig, 1972). Deeply incised palaeovalleys, typically 500 m deep and several kilometers wide, have been described in the Tarija and Escarpment Formations (Fig. 6; (Helwig, 1972; Salinas *et al.*, 1978; Tankard *et al.*, 1995). The palaeovalley infills have been interpreted as continental tillites and subaerial meltwater channels, deposited by ice margins advancing and retreating, respectively (Helwig, 1972; Salinas *et al.*, 1978). The ice masses flowed across the Chaco Basin and were fed from ice centres to the S and E, situated within the Brazilian Craton (Helwig, 1972; Salinas *et al.*, 1978). To the contrary, Eyles *et al.* (1995) stress the importance of marine sedimentation and the paucity of evidence for any direct glacial influence on sedimentation. The Late Devonian-Early Carboniferous orogeny and Gondwana glaciations develop simultaneously and therefore, are usually considered to be associated with each other (Amos, 1972; Eyles and Eyles, 1993; Eyles, 2008).

DATA AND METHOD

The dataset consists of 9000 km of 2D seismic lines and 4 wells tied to the seismic (Fig. 1). Seismic interpretations were carried out based on the principles of seismic stratigraphy (Vail *et al.*, 1977). Seismic units are identified based on reflection terminations and the configurations of seismic reflections (Fig. 7). The units can be mapped in 3D throughout the basin thanks to the extensive coverage of the seismic data.

Additional information (datings, e-logs) were obtained from boreholes that sampled the Carboniferous units (Fig. 8). The gamma ray logging records the radioactivity of a formation. Shales (or clay-minerals) commonly have a relatively high gamma radioactive response and, consequently, gamma ray logs are considered to reflect the main grain size. Sonic logs measures the velocity of sound waves in rock. In complement to the gamma ray, sonic logs help to determine the lithology. The sonic logs have also been used to tie the well to the seismic lines.

The Paleozoic strata have been deformed after their deposition (Izozog deformation). As the tectonic activity is supposed to have occurred at least after the Devonian, a Silurian horizon (Figs. 3 and 4) has been used as a datum for the flattening of the seismic lines. At a regional scale, this method allows restoring the genuine morphology of the seismic stratigraphic surfaces.

This paper focuses on the upper part of the Carboniferous succession where two major stratigraphic surfaces have been picked and correlated throughout the basin (surfaces 4 and 5; Fig. 7). The geometric parameters of the observed incisions marked on these surfaces have been extracted from the studied (1) seismic strike sections for the width and depth, and (2) the flattened regional maps of the picked surfaces to define their longitudinal extension and drainage patterns. The described methodology allowed a detailed investigation of the seismic architecture of the Late Palaeozoic deposits of the Chaco Basin.

IZOZOG DEFORMATION

Glacial activity is commonly considered to be associated with a tectonic trigger (Eyles, 2008). However, the presence of tectonic activity in the Chaco Basin during the deposition of the glaciogenic rocks of Late Palaeozoic is debatable. Previous mapping of the Carboniferous palaeovalleys (Fig. 6) suggested an influence of the Izozog High during their formation. Eyles *et al.* (1995) attributed the convergent direction of palaeovalleys to their formation in a confined basin.

Two main observations suggest, however, that the Izozog High formed after the Carboniferous, i.e. after the formation of the palaeovalleys. The first observation concerns the stratigraphic relationships between the Palaeozoic and the Mesozoic units. A major unconformity can be recognized on the seismic lines (yellow line, Fig. 3). This unconformity is of a regional extent and separates the Palaeozoic units from the Mesozoic ones (Fig. 8). The unconformity is deeply incised into the Palaeozoic rocks at the apex of the Izozog High (Fig. 5). The topography of the High is progressively onlapped and concealed by the Mesozoic deposits (Fig. 3). This erosion/deposition relationship is the evidence of a post-Palaeozoic tectonic uplift in the Izozog area. The second observation concerns the orientation of the Carboniferous palaeovalleys. The new maps of the palaeovalleys (Figs. 9 and 10) do not show any deflection over the Izozog High. On the contrary, the palaeovalleys are progressively more eroded toward the Izozog apex, indicating that the uplift is postdating the formation of the incisions.

PALAEOVALLEY MORPHOLOGIES

Ice masses are else flowing from highland areas (mountains) or lowland areas (quiet basins) and accordingly generate different types of valleys. In the Chaco Basin, the ice centres are situated onto the Brazilian craton (Helwig, 1972; Salinas *et al.*, 1978). Therefore, the here analysed glacial palaeovalleys are associated with lowland-ice sheets. Lowland-ice sheets usually generate three types of glaciogenic incisions visible on the seismic data (Table 1): (1) the tunnel valleys, (2) the ice stream cross-shelf troughs and (3) the fjords (not restricted to lowlands). (1) The tunnel valleys are frequently sinuous and are known to be organised in anastomosing to tributary branching patterns (Huuse and Lykke-Andersen, 2000). They reach up to 4 km in width, 500 m in depth, 100 kilometres in length (e.g. (O'Cofaigh, 1996; Huuse and Lykke-Andersen, 2000; Ghienne *et al.*, 2003; Praeg, 2003)). Tunnel valleys have been mainly observed in unconsolidated sediments but can also incise rocks. It has been assumed that tunnel valleys originate from subglacial pressurised meltwater incisions (Wingfield, 1990; Brennand and Shaw, 1994; O'Cofaigh, 1996). (2) The ice-stream cross-shelf troughs are U-shaped as well, they reach extreme widths (100' of km) and lengths (>600 km). Usually, their depths are subconstant along their flow lines at a regional scale, but they can vary significantly in tectonically active areas. On relatively passive margins like offshore Norway, they generate incisions between 200 and 500 metres deep and at least 10 km wide (Ottesen *et al.*, 2008). These cross-shelf troughs are preferentially incised into soft unconsolidated sediments (e.g. the Norwegian channel northern boundary on hard rocks (Ottesen *et al.*, 2005)). (3) As opposed to of (1) and (2), the fjords are deep glacial valleys incised into bedrock. Their depth reaches several kilometres while they stay relatively narrow in width (<10 km). Their longitudinal extent is 10's of kilometres but rarely exceeds 100 km (maps in Ottesen *et al.*, 2008 for comparison). The drainage patterns of fjords are relatively straight, often guided by faults. They have a tendency to follow the structural grain onto the basement. Fjords often correspond to the upstream part of ice-streams where they incise crystalline bedrock (Ottesen *et al.*, 2005; Ottesen *et al.*, 2008).

In the Chaco Basin, the seismic analysis of the Late Palaeozoic sedimentary architecture shows an intricate succession of unconformities bounding the base of depositional sequences (Fig. 7). The peculiarity of these unconformities is the presence of large palaeovalleys, predominantly in the upper part of the Carboniferous succession. Both U- and V-shaped palaeovalleys are observed (Fig. 11). Their width ranges between 3 and 21 km with a mean width of 7.36 km (n: 24, standard deviation: 4.19 km). The incisions are deep with 500-700 m between the shoulders and the bottom of the thalweg. Two Upper Carboniferous surfaces have been mapped in detail (surfaces 4 and 5; Figs. 9, 10) and compared (Fig. 12). The mapped incisions are visible between the western limit of the dataset to the West and the Izozog High to the East, where they have been removed by erosion (Figs. 9, 10). They form extremely elongated depressions that were at least >100 km long. The palaeovalleys of surface 4 are subparallel with a predominent SE-NW direction. The palaeovalleys of surface 5 present a radial pattern with two different orientations in the North

(SE-NW direction) and in the West (E-W direction, Fig. 13) of the Chaco Basin. The surface 5 shows two valleys merging and diverging twice to the South (Fig. 10).

The geometric parameters of the Chaco Basin incisions have been summarised and compared with the three known types of glaciogenic valleys (Table 1). Table 1 highlights that the studied glaciogenic incisions share characteristics with different types of glacial palaeo-valleys under lowland-ice sheet conditions:

- The section shapes are comparable with fjords, indicating a mixed process abrasion (U-shape) and hydraulic (V-shape).
- The widths are clearly over the width of tunnel valleys but do not permit discriminating between fjords and cross-shelf troughs.
- The depths are similar to fjords and cross-shelf troughs but bigger than tunnel valleys.
- The lengths are comparable with ice stream troughs. Especially knowing that the lengths are underestimated because of the dataset extent and the Izozog High.
- The basement is assumed to be unlithified as in the tunnel valleys and cross-shelf troughs.
- They are straight to slightly sinuous like cross-shelf troughs.
- Except for two valleys on surface 5, they show no branching or anastomosing drainage patterns. This characteristic is also shared with cross-shelf troughs.

The size of the Chaco basin incisions rules out their possible interpretation as tunnel valleys. The anastomosed network to the South of Surface 5 (Fig. 10) is instead interpreted to result from the cross-cut between two generations of glacial valleys. This cross-cut is not resolvable with the available seismic data. However, it is difficult to discriminate whether the incisions represent cross-shelf troughs or fjords. The lengths of the Chaco incisions are an order of magnitude bigger than fjords. On the other hand, the section shapes and the depths are closer to fjords than to cross-shelf troughs. The Scandinavian ice sheet shows spatial transition between fjords on crystalline and lithified basements to cross-shelf troughs on sediments (Ottesen, 2008).The shared characteristics of both cross-shelf troughs and fjords with the Chaco Basin valleys is therefore, interpreted to be the result of basement variations probably linked to varying lithification degrees of the subglacial substrate. These lithological variations are probably favouring abrasion-dominated processes (unconsolidated; cross-shelf trough type) or hydraulic-dominated incisions (lithified: fjord type).

The comparison of the drainage patterns on surfaces 4 and 5 shows a change in the orientation of the Chaco Basin incisions through time (Fig. 12). This indicates that the palaeoglaciological setting evolved between the two generations. The first generation (surface 4) is well organised with parallel troughs whereas the second generation of valleys (surface 5) radiates from a c. NW-SE axis (Fig. 12). This pattern change has been be interpreted to reflect one large ice mass forming surface 4 and individual ice sheets forming surface 5. The dispersive pattern may alternatively be the result of an ice margin closer during the formation of the surface 5 than the surface 4. This drainage pattern evolution at a regional scale is probably the result of a tectono-climatic evolution affecting the ice centres sourcing the Chaco Basin ice sheets during the Late Carboniferous.

PALAEOVALLEYS INFILL

The most detailed dataset concerns the sediments filling the palaeovalleys of surface 5. The sediments have been attributed to the Escarpment and the San Telmo Formations (Fig. 2, 8). Consequently, the analysis is focused on this stratigraphic interval based by surface 5 and topped by the next glaciogenic unconformity. The interval consists of three distinct sedimentary units with specific seismic facies, wireline log signatures, and sedimentary environments (Fig. 14). Facies 1 occurs at the base of the palaeovalleys (Fig. 14). It corresponds to a chaotic seismic facies suggesting an unsorted and unstratified accumulation of sediments. Gamma ray and sonic logs typically associated with diamictites can be observed (Fig. 14). Facies 2 is overlying Facies 1 (Fig. 14). Facies 2 is made of prograding clinoforms that can be seen downlapping on Facies 1. Gamma ray logs indicate coarsening-up shale to sandstone cycles (Fig. 14). On the seismic data, Facies 3 overlays unconformably facies 2. Facies 3 has a channelised to slightly chaotic seismic facies. It is characterized by fining-upward cycles of sandy units on gamma ray logs.

Facies 1, 2 and 3 have been interpreted as tills, delta progradations and fluvial deposits, respectively. This interpretation is supported by the field observations of the outcrop analogue (Fig. 14). Consequently, it is suggested that after the subglacial incision of palaeovalleys, the sedimentary environment passed through different phases: (1) subglacial to ice-marginal environment forming the till when ice is in the Chaco Basin, (2) the ice leaves the basin (3) the remnant glacial topography is progressively buried by an advancing fluvio-deltaic system. This sedimentary system which concealed the 500-700m deep valleys was probably fed by ice margins further inland to the SE.

Analogues to the palaeovalleys infill patterns in the Chaco Basin can be found within Upper Ordovician palaeovalleys. The Ordovician valleys are filled by glacial sequences usually showing a motif with coarse-grained deposits (conglomerates, diamictites) at the base, passing upsection into prograding deltas and further into aggrading fluvial deposits (Le Heron *et al.*, 2009). The nature of the fill varies in style depending upon the palaeogeographic setting (Le Heron *et al.*, 2004). In proximal settings, non-marine glaciofluvial sandstones overlie an initial fill of ice-proximal deposits. In deeper water settings, the initial, locally developed, ice-proximal deposits are overlain by a transition from ice-distal diamictites to sand-dominated underflow fans. A deposition of this fill during deglaciation or marine transgression has been suggested (Powell *et al.*, 1994; Ghienne and Deynoux, 1998; Le Heron *et al.*, 2004). Considering the similarities between the successions in the Chaco Basin and the Ordovician, the palaeovalley infill of the Chaco Basin is considered to correspond to a glacial sequence. As hundreds of metres of deltaic sediments overlay the basal till (Fig. 14), this glacial sequence is first developed in relatively deep water directly after ice retreat.

Terminal moraines are important indicators of former ice-front positions. Studies of exposed marine moraines have demonstrated that their internal facies architectures bear a high-resolution record of ice-front evolution, with direct implications for glacier dynamics and regional paleoclimatic conditions (Lønne, 1995, 1997). Lønne (1995, 2001) and Lønne *et al*. (2001) have synthesized the development of marine ice-contact systems in the form of an allostratigraphic model. The model has implies a sedimentary architecture comparable to the sedimentary infill observed in the Chaco Basin palaeovalleys. In the southern part of the Chaco Basin, deltaic deposits (Facies 2) prograde in opposite directions (Fig. 15). In the Oslofjorden, the area between two clinoform orientations localise a former ice front (Lønne, 2001). Despite of the difference in the scale, this Quaternary example serves as an analogue; the pattern of clinoform orientations in the Chaco Basin is interpreted to mark the location of an ice front of a Late Carboniferous age (Fig. 16). Based on the Oslofjorden analogue, the glaciological and sedimentary evolution is deduced from the seismic analysis of surface 5 and its relative glacial sequence is summarised in a conceptual model presented in Fig. 16. The following multistage formation of the glacial sequence of surface 5 is suggested in the model: (1) the ice advance and the creation of the valleys; (2) a still stand during ice recession in the basin and the generation of the southward-dipping proglacial fan-delta; (3) the recession of the ice from the basin associated with the isostatic uplift of the former ice front, leading to the reworking of the uplifted area and the creation of the northward-dipping clinoforms; (4) some minor readvance permitting the development of another fluvio-deltaic system prograding to the South and blanketing the northward-dipping clinoforms; and (5) the final ice recession associated with a last advance of the fluvio-deltaic system on top of the glacial sequence. This model honours the observed complexity of the glacial sequence and its potential palaeo-glaciological record. In addition to ice-flow patterns deduced from the valley orientations, the localisation of ice-front positions and their consecutive depocentres are good constrains for understanding the evolution of ancient ice sheets.

CONCLUSIONS

The Late Palaeozoic sedimentary architecture of the Chaco Basin (Bolivia) is characterized by a succession of erosional surfaces and seismic sequences. This sedimentary architecture records the Late Palaeozoic glaciation events, and the modality of the ice age in the area. The main results of this study are:

- The Izozog High did not influence the Late Palaeozoic palaeovalley orientations. Considering the progressive onlap of the Late Cenozoic deposits on the High, the Izozog Uplift is considered to be postdating the ice age and predating the Cretaceous fluvial deposits.
- Erosional surfaces present different morphologies from the base to the top of the succession. These surfaces can be flat (base of Carboniferous) whereas they form very large palaeovalleys (up to 20 km wide and 700 m deep) in the upper part of the succession.
- A lowland glacial environment is suggested, but the erosional processes responsible for the incisions remain debatable. A coupling between subglacial meltwater and mechanical abrasion processes is considered as a possible explaination for the observed valley geometries. In addition, the amount of meltwater at the base of the glacier (cold-/ warm-based or polythermal ice sheet), the nature and the lithification degree of the incised sediments probably induced the variability of the glacial erosional surfaces.
- The analysis of the glacial surface successions highlights the glacial history of the area, including ice flow rotations associated with changes in the glaciological parameters of the ice sheets.

- The palaeovalleys are covered by diamictites in the deepest part of the thalwegs overlain by deltas fed by fluvial depositional systems. As well as the Ordovician glacial sequences, the sand-prone Chaco Basin sediments present a good reservoir potential. This succession, corresponding to a glacial sequence, has been interpreted as the effect of glacier retreat. Depending of the distance to the ice margins, all or parts of the facies can be observed.

This paper aims at showing the intricate architecture of the glaciation record in the Late Palaeozoic sediments of the Chaco Basin. Although the origins of the glaciogenic features need to be investigated in more detail, this dataset highlights the importance of constructing a precise seismic stratigraphy for ancient ice ages. This work unravels a part of the glacial history in the area, built up of distinct events with different glacial settings and, thus, different climatic and tectonic triggers. This study localises ancient grounding lines of ice fronts which are palaeohighs containing proximal sandy facies. As they form isolated coarse-grained clastic depocentres, they represent good targets for hydrocarbon exploration. Extending the analysis on each glacial depositional sequence is the next step to establish the context of the Late Palaeozoic ice age and its petroleum potential in the Chaco Basin.

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FIGURE CAPTIONS

Fig. 1. Topographic map of Bolivia and subsurface dataset used for this study. Dotted lines delimit the major tectonic provinces.

Fig. 2. Generalised stratigraphic column of the southern sub-Andean region with the source rocks, proven sub-Andean reservoirs and local ice sheet development. Modified from Dunn *et al.*1995.

Fig. 3. Time-depth of the top of the Silurian unit showing the location of the Izozog High southeast of the Chaco Basin.

Fig. 4. Regional seismic lines showing the deformation of Paleozoic units by the Izozog High and the onlap of Mesozoic and Cenozoic strata on the High.

Fig. 5. Time-thickness maps of Paleozoic and post-Paleozoic units in the Chaco Basin. Thickness variations of Devonian, Carboniferous and Permian units are the result of erosion in the Izozog area after their deposition. The N-S strike orientation of the Mesozoic-Cenozoic depocentre highlights the influence of the Andean deformation.

Fig. 6. Palaeovalleys described in the Carboniferous unit of the Chaco Basin Modified from (Helwig, 1972; Salinas *et al.*, 1978; Tankard *et al.*, 1995).

Fig. 7. Erosional surfaces identified in the Carboniferous. Palaeovalleys of surfaces 4 and 5 are well imaged and have been precisely mapped (Fig. 10 and 11). TC: Top of Carboniferous. BC: Base of Carboniferous. Location of seismic profile on Fig. 1.

Fig. 8. Datation of seismic reflectors with boreholes. Location of boreholes on figure 1.

Fig. 9. Thickness map (in TWTT, left) between a continuous reference surface (top Devonian) and surface 4 highlighting palaeovalleys of surface 4 (right).

Fig. 10. Thickness map (in TWTT, left) between a continuous reference surface (top Devonian) and surface 5 highlighting palaeovalleys of surface 5 (right).

Fig. 11. Seismic lines showing palaeovalleys of surface 5. TC: Top of the Carboniferous. BC: Base of the Carboniferous.

Fig. 12. Comparison between palaeovalleys directions of surface 4 and surface 5.

Fig. 13. Detail of a palaeovalley of surface 5.

Fig. 14. Palaeovalleys infill and corresponding seismic facies, sedimentary environment and electro-facies. GR: Gamma Ray. DT: Sonic.

Fig. 15. Seismic profile showing progradational facies (facies 2) in two different directions (toward the North and toward the South). This sedimentary pattern could indicate the proximity of an ice front. TC: Top of the Carboniferous. BC: Base of the Carboniferous. Location of seismic profile on figure 1.

Fig. 16. Conceptual model to explain the Carboniferous sedimentary depositional pattern of the Chaco Basin. Modified from Lønne *et al*. 2001.

Table. 1. Comparison between palaeovalleys observed in the Chaco Basin and different types of glaciogenic incisions associated with lowland-ice sheets.* From "pure" ice streams (Bennett, 2003). M. =Mean.

REFERENCES

Amos, A. J., 1972, Las Cuencas Carbónicas y Pérmicas de Argentina: *Anales Brasileños de Ciencias*, **44**, 21-36.

Bennett, M. R., 2003, Ice streams as the arteries of an ice sheet: their mechanics, stability and significance: *Earth Science Reviews*, **61**, 309-339.

Brennand, T. A., & Shaw, J., 1994, Tunnel channels and associated landforms, south-central Ontario: their implication for ice-sheet hydrology: *Canadian Journal of Earth Sciences*, **31**, 505-522.

Caputo, M. V., & Crowell, J. C., 1985, Migration of glacial centers across Gondwana during Paleozoic Era: *Geological Society of America Bulletin*, **96**, 1020-1036.

Caputo, M. V., de Melo, J. H. G., Streel, M., & Isbell, J. L., 2008, Late Devonian and Early Carboniferous glacial records of South America, *In:* Fielding, C. R., Frank, T. D., & Isbell, J. L., (eds.), *Resolving the Late Paleozoic Ice Age in Time and Space*: Geological Society of America Special Paper, **441**, 161-173.

Crowell, J. C., & Frakes., L. A., 1975, The late Paleozoic glaciation, *In:* Campbell, K. S. W., (ed.), *Gondwana Geology*: Australian National University Press, *Canberra*, 313-331.

Decelles, P. G., & Horton, B. K., 2003, Early to Middle Tertiary foreland basin development and the history of Andean crustal shortening in Bolivia: *Geological Society of America Bulletin*, **115**, 58-77.

Du Toit, A. L., 1937, Our Wandering Continents: Edinburgh, Oliver and Boyd.

Dunn, J. F., Hartshorn, K. G., & Hartshorn, P. W., 1995, Structural styles and hydrocarbon potential of the sub-andean thrust belt of southern Bolivia, *In:* Tankard, A. J., Suàrez, S., & Welsink, H. J., (eds.), *Petroleum basins of South America*: American Association of Petroleum Geologists, *Tulsa*, **Memoir 62**, 523-543.

Eyles, N., 2008, Glacioepochs and the supercontinent cycle after ~3.0 Ga: tectonic boundary conditions for global cooling: *Palaeogeography, Palaeoclimatology, Palaeoecology*, **258**, 89-129.

Eyles, N., & Eyles, C. H., 1993, Glacial geologic confirmation of an intraplate boundary in the Paraná basin of Brazil: *Geology*, **21**, 459-462.

Eyles, N., Gonzalez Bonorino, G., França, A. B., Eyles, C. H., & Lopez Paulsen, O., 1995, Hydrocarbon-bearing late Paleozoic glaciated basins of southern and central South America, *In:* Tankard, A. J., Suàrez, S., & Welsink, H. J., (eds.), *Petroleum basins of South America*: American Association of Petroleum Geologists, *Tulsa*, **Memoir 62**, 165-183.

Ghienne, J. F., & Deynoux, M., 1998, Large-scale channel fill structures in Late Ordovician glacial deposits in Mauritania, western Sahara.: *Sedimentary Geology*, **119**, 141-159.

Ghienne, J. F., Deynoux, M., Manatschal, G., & Rubino, J. L., 2003, Palaeovalleys and fault-controlled depocentres in the Late-Ordovician glacial record of the Murzuq Basin (central Libya) *Comptes Rendus Geosciences*, **335**, 1091-1100

Gohrbandt, K. H. A., 1992, Paleozoic paleogeographic and depositional developments on the central proto-Pacific margin of Gondwana : their importance to hydrocarbon accumulation: *Journal of South American Earth Sciences*, **6**, 267-287.

Hambrey, M. J., & Harland, W. B., 1981, Earth's Pre-Pleistocene Glacial Record: Cambridge, Cambridge University Press.

Helwig, J., 1972, Stratigraphy, sedimentation, paleogeography, and paleoclimates of Carboniferous ("Gondwana") and Permian of Bolivia: *American Association of Petroleum Geologists Bulletin*, **56**, 1008-1033.

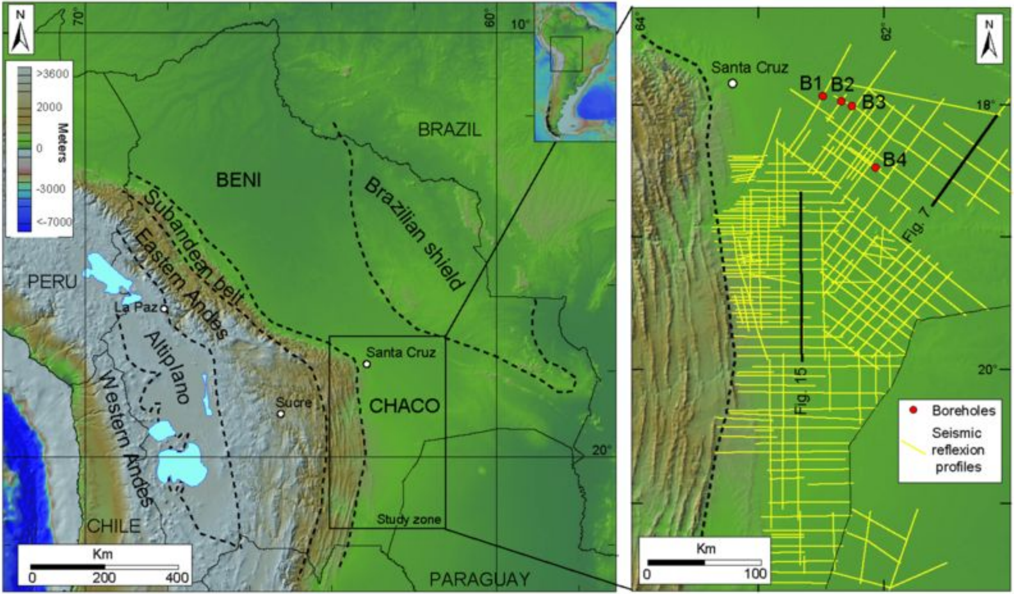
Huuse, M., & Lykke-Andersen, H., 2000, Large-scale glaciotectonic thrust structures in the eastern Danish North Sea, *In:* Maltman, A., Hambrey, M., & Hubbard, B., (eds.), *Deformation of Glacial Materials*: Geological Society Special Publications, *London*, **176**, 293-305.

Le Heron, D., Craig, J., & Etienne, J. L., 2009, Ancient glaciations and hydrocarbon accumulations in North Africa and the Middle East.: *Earth-Science Reviews*, **93**, 47-76.

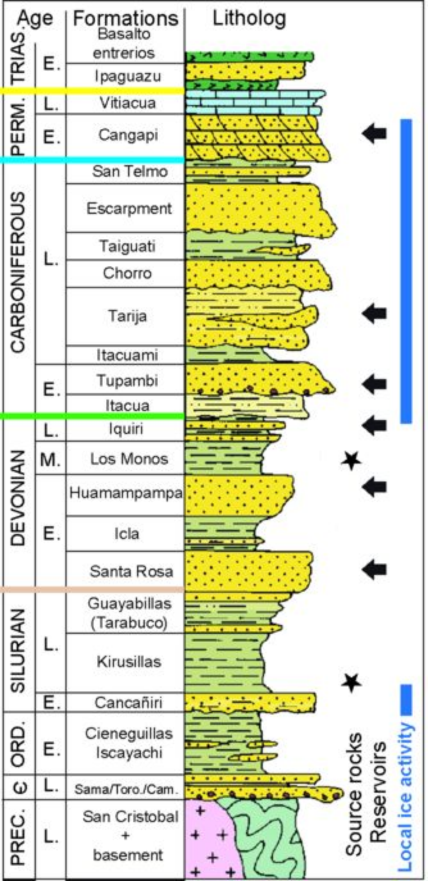
Le Heron, D., Sutcliffe, O., Bourgig, K., Craig, J., Visentin, C., & Whittington, R., 2004, Sedimentary architecture of Upper Ordovician tunnel valleys, Gargaf Arch, Lybia: implications for the genesis of a hydrocarbon reservoir: *GeoArabia*, **9**, 137-160.

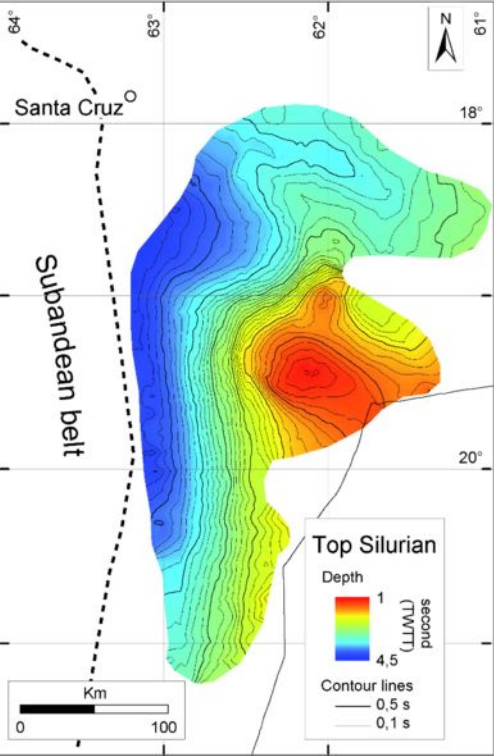
Lønne, I., 1995, Sedimentary facies and depositional architecture of ice-contact glaciomarine systems: *Sedimentary Geology*, **98**, 13-43.

-, 1997, Facies characteristics of a proglacial turbiditic sand-lobe at Svalbard: *Sedimentary Geology*, **109**, 13-35.
-, 2001, Dynamics of marine glacier termini read from moraine architecture: *Geology*, **29**, 199-202.
Lønne, I., Nemec, W., Blikra, L. H., & Lauritsen, T., 2001, Sedimentary Architecture and Dynamic Stratigraphy of a Marine Ice-Contact System: *Journal of Sedimentary Research*, **71**, 922-943.
O'Cofaigh, C., 1996, Tunnel valley genesis: *Progress in Physical Geography*, **20**.
Ottesen, D., Dowdeswell, J. A., & Rise, L., 2005, Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57°–80°N). *Geological Society of America Bulletin*, **117**, 1033-1050.
Ottesen, D., Stokes, C. R., Rise, L., & Olsen, L., 2008, Ice-sheet dynamics and ice streaming along the coastal parts of northern Norway: *Quaternary Science Reviews*, **27**, 922-940.
Powell, J. H., Moh'd, B. K., & Masri, A., 1994, Late Ordovician-Early Silurian glaciofluvial deposits preserved in palaeovalleys in South Jordan.: *Sedimentary Geology*, **89**, 303-314.
Praeg, D., 2003, Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin-high resolution from low frequencies *Journal of Applied Geophysics*, **53**, 273-298
Salinas, C., Oblitas, J., & Vargas, C., 1978, Exploration del Sistema Carbonifero en la Cuenca Oriental de Bolivia: *Revista Tecnica Yacimientos Petroliferos Fiscales Bolivianos*, **7**, 5-49.
Sempere, T., 1995, Phanerozoic evolution of Bolivia and adjacent regions, *In:* Tankard, A. J., Suàrez, S., & Welsink, H. J., (eds.), *Petroleum basins of South America*: American Association of Petroleum Geologists, *Tulsa*, **Memoir 62**, 207-230.
Sempere, T., Herail, G., Oller, J., & Bonhomme, M. G., 1990, Late Oligocene-Early Miocene major tectonic crisis and related basins in Bolivia: *Geology*, **18**, 946-949.
Tankard, A. J., Uliana, M. A., Welsink, H. J., Ramos, V. A., Turic, M., Franca, A. B., Milani, E. J., de Brito Neves, B. B., Eyles, N., Skarmeta, J., Santa Ana, H., Wiens, F., Cirbian, M., Lopez Paulsen, O., Germs, G. J. B., De Wit, M. J., Machacha, T., & McG. Miller, R., 1995, Structural and tectonic controls of basin evolution in southwestern Gondwana during the Phanerozoic, *In:* Tankard, A. J., Suàrez, S., & Welsink, H. J., (eds.), *Petroleum basins of South America*: American Association of Petroleum Geologists, **Memoir 62**, 5-52.
Uba, C. E., Heubeck, C., & Hulka, C., 2006, Evolution of the late Cenozoic Chaco foreland basin, Southern Bolivia.: *Basin Research*, **18**, 145-170.
Vail, P. R., Mitchum, R. M., Jr., & Thompson, S., III., 1977, Seismic stratigraphy and global changes of sea-level, part 3: Relative changes of sea level from coastal onlap, *In:* Payton, C. E., (ed.), *Seismic Stratigraphy - Applications to hydrocarbon exploration*: American Association of Petroleum Geologists, *Tulsa*, **Memoir 26**, 63-81.
Wegener, A., 1915, Die entstehung der kontinente und ozeane (The origin of continents and oceans): New-York, Dutton and Co.
Wingfield, R. T. R., 1990, The origin of major incisions within the Pleistocene deposits of the North Sea: *Marine Geology*, **91**, 31-52.

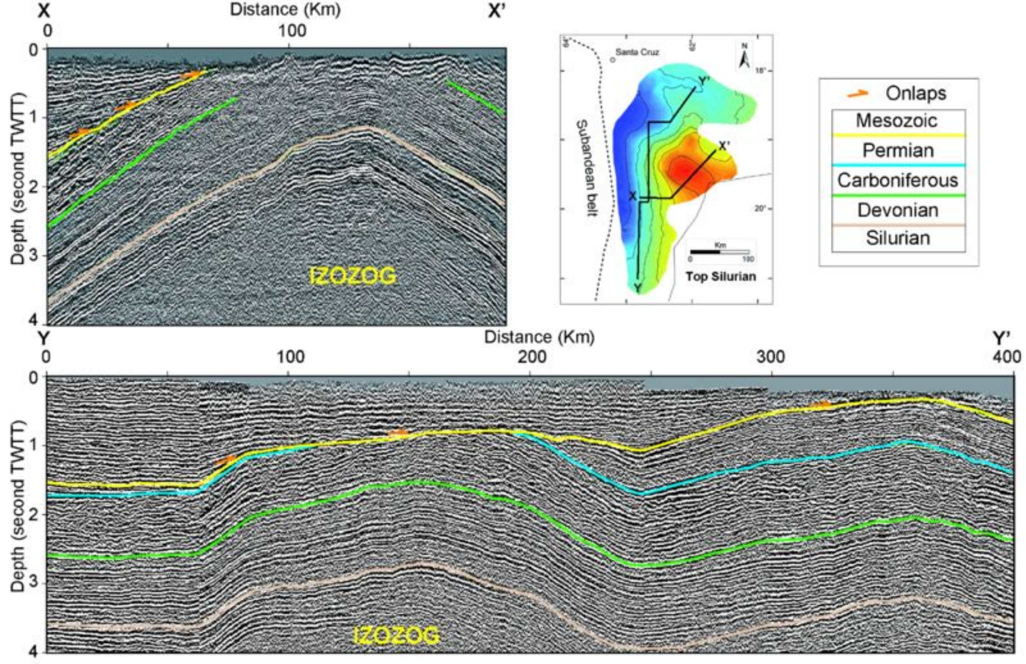


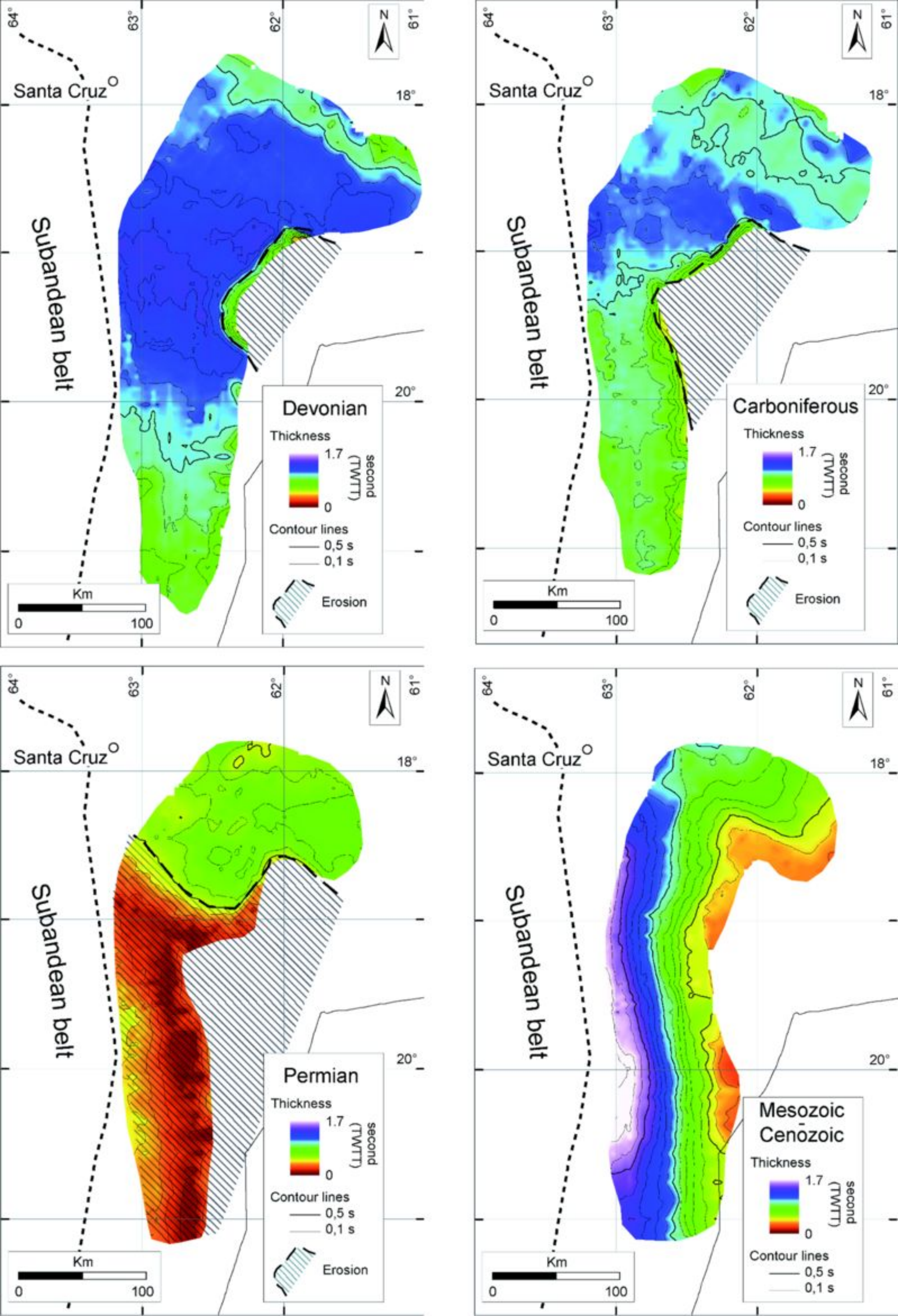
N
70°
60°
10°
>3600
2000
0
-3000
<-7000
Meters
BRAZIL
BENI
Brazilian shield
Subandean belt
Eastern Andes
PERU
La Paz
Altiplano
Western Andes
Santa Cruz
Sucre
CHACO
CHILE
20°
Study zone
PARAGUAY
Km
0
200
400
64°
62°
Santa Cruz
B1
B2
B3
B4
18°
Fig. 7
Fig. 15
20°
Boreholes
Seismic reflexion profiles
Km
0
100


Age
Formations
Litholog
TRIAS.
E.
Basalto entrerios
Ipaguazu
PERM.
L.
Vitiacua
E.
Cangapi
CARBONIFEROUS
L.
San Telmo
Escarpment
Taiguati
Chorro
Tarija
Itacuami
E.
Tupambi
Itacua
DEVONIAN
L.
Iquiri
M.
Los Monos
E.
Huamampampa
Icla
Santa Rosa
SILURIAN
L.
Guayabillas (Tarabuco)
Kirusillas
E.
Cancañiri
ORD.
E.
Cieneguillas Iscayachi
Є
L.
Sama/Toro./Cam.
PREC.
L.
San Cristobal + basement
Source rocks
Reservoirs
Local ice activity

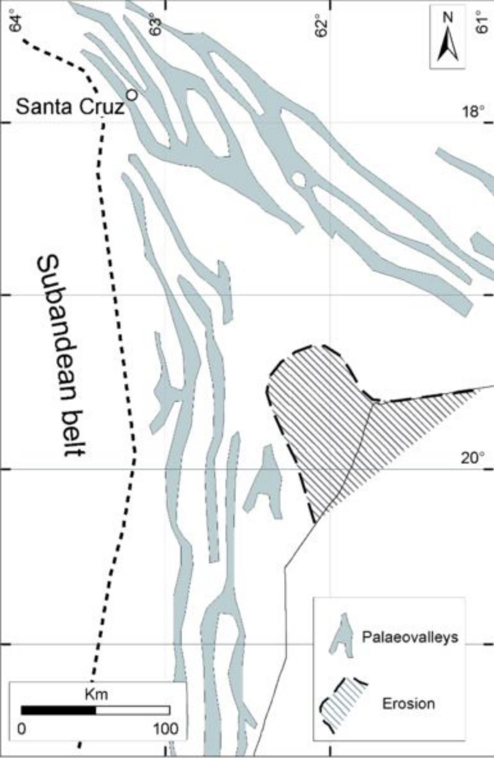


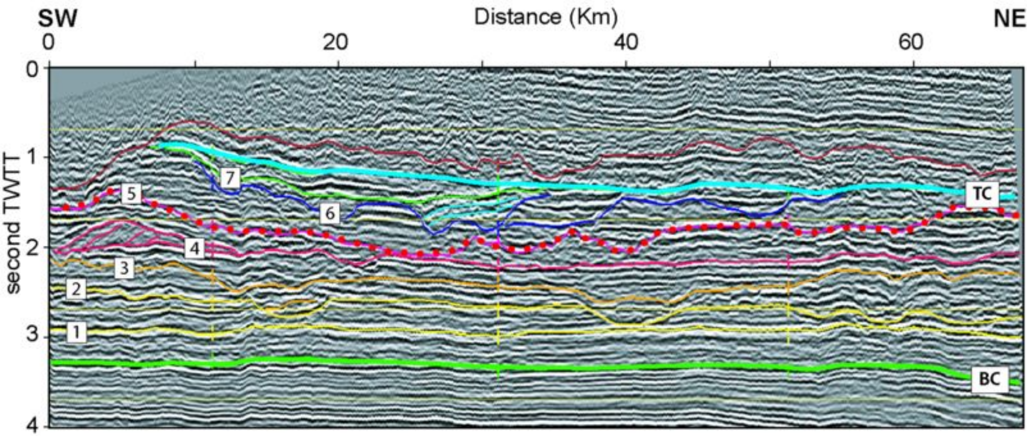
64°
63°
62°
61°
N
Santa Cruz
18°
20°
Subandean belt
Top Silurian
Depth
1
4,5
second (TWTT)
Contour lines
0,5 s
0,1 s
Km
0
100


X
X'
Distance (Km)
0
100
Depth (second TWTT)
0
1
2
3
4
IZOZOG
Santa Cruz
Subandean belt
Y'
X'
X
Y
18°
20°
Km
0
100
Top Silurian
Onlaps
Mesozoic
Permian
Carboniferous
Devonian
Silurian
Y
Y'
Distance (Km)
0
100
200
300
400
Depth (second TWTT)
0
1
2
3
4
IZOZOG

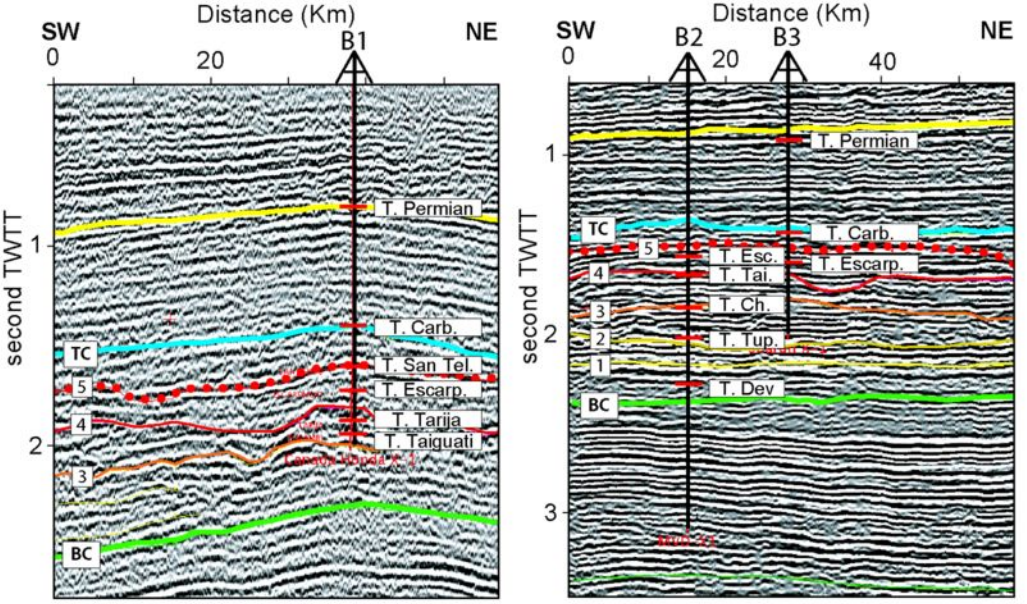


64°
63°
62°
61°
N
Santa Cruz
18°
20°
Subandean belt
Devonian
Thickness
1.7
0
second (TWTT)
Contour lines
0,5 s
0,1 s
Erosion
Km
0
100
Carboniferous
Permian
Mesozoic - Cenozoic

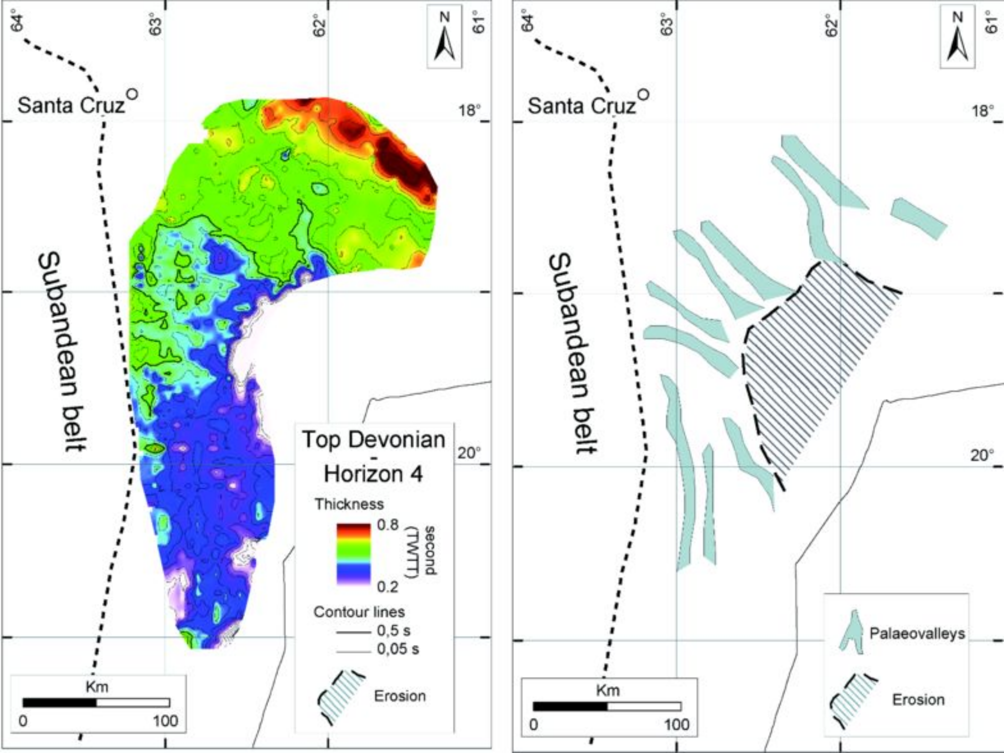

64°
63°
62°
61°
N
Santa Cruz
18°
Subandean belt
20°
Km
0
100
Palaeovalleys
Erosion

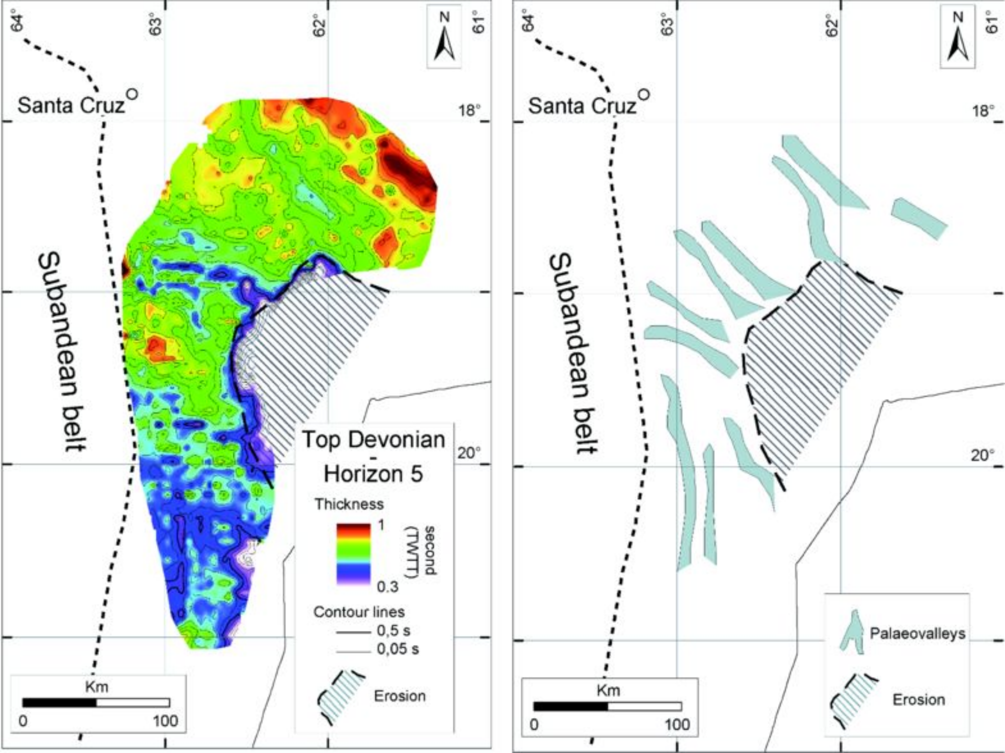


SW
Distance (Km)
NE
0
20
40
60
0
1
2
3
4
second TWTT
1
2
3
4
5
6
7
TC
BC

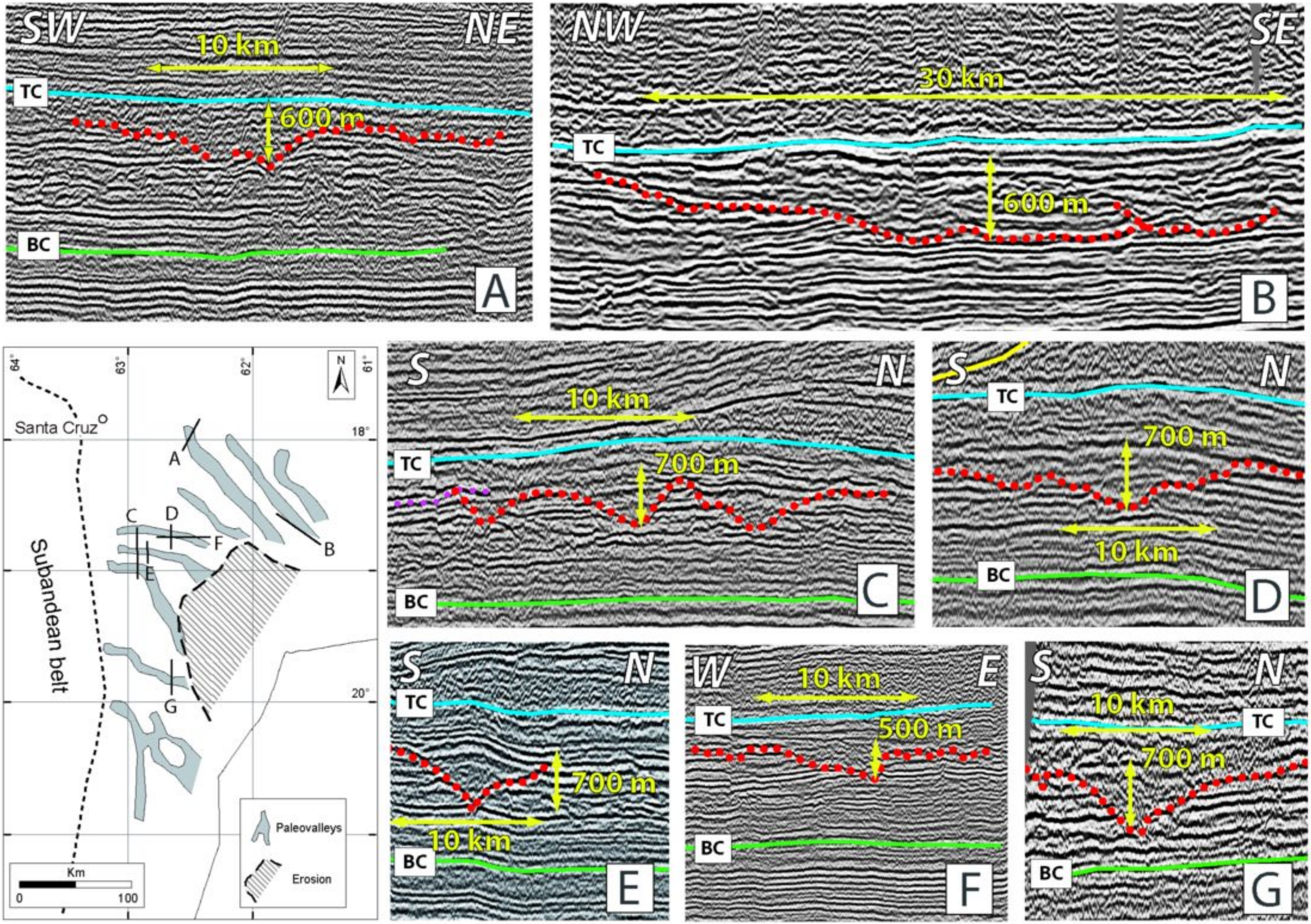


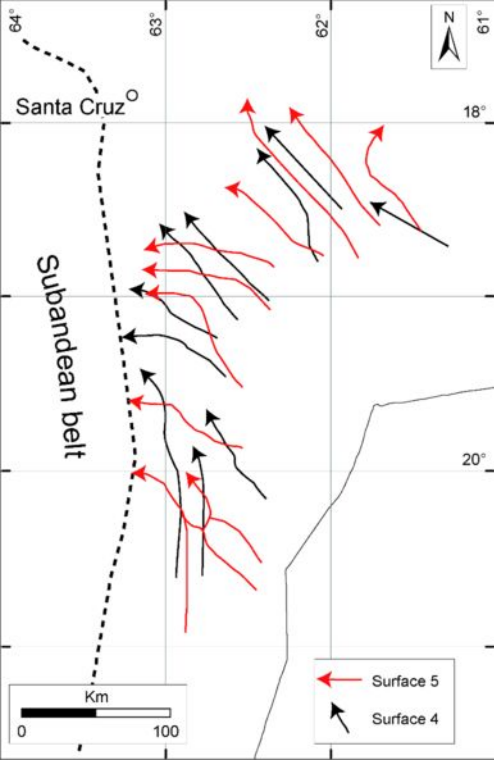
Distance (Km)
SW
NE
B1
0
20
second TWTT
1
2
T. Permian
T. Carb.
TC
T. San Tel.
5
T. Escarp.
4
T. Tarija
T. Taiguati
3
BC
Distance (Km)
SW
NE
B2
B3
0
20
40
second TWTT
1
2
3
T. Permian
TC
T. Carb.
5
T. Esc.
T. Escarp.
4
T. Tai.
3
T. Ch.
2
T. Tup.
1
T. Dev
BC


64°
63°
62°
61°
N
Santa Cruz
18°
20°
Subandean belt
Top Devonian - Horizon 4
Thickness
0.8
0.2
second (TWTT)
Contour lines
0,5 s
0,05 s
Erosion
Km
0
100
Palaeovalleys

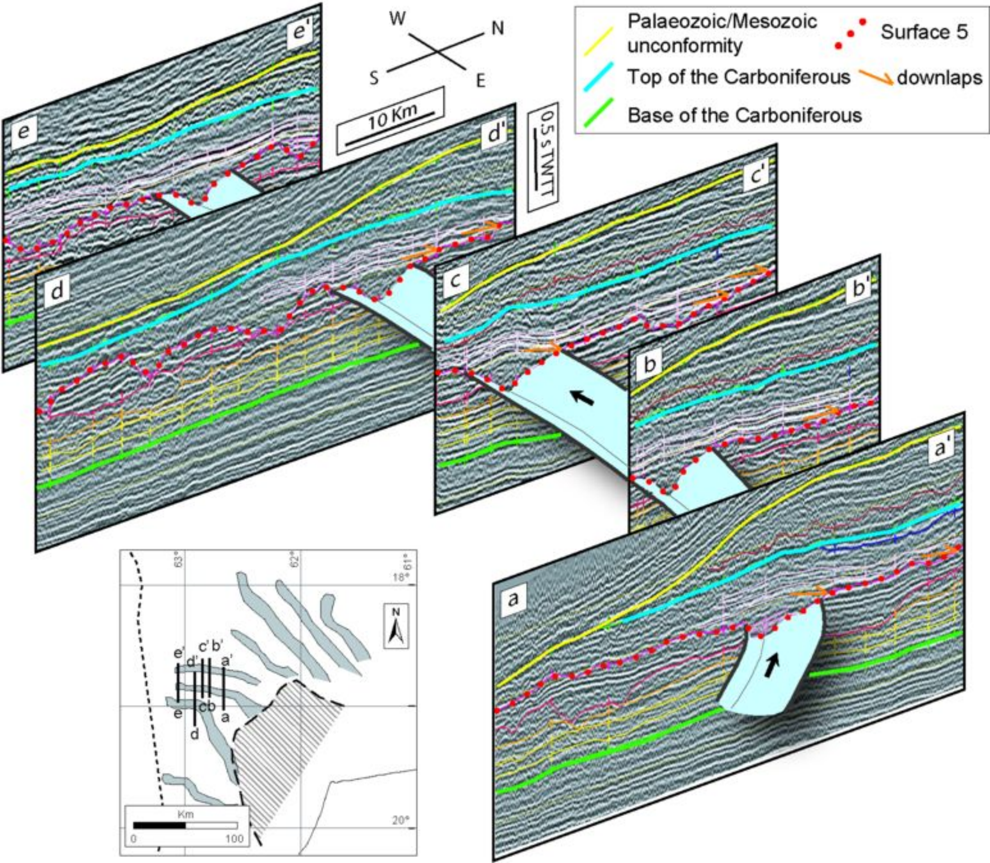


64°
63°
62°
61°
N
Santa Cruz
18°
Subandean belt
20°
Top Devonian - Horizon 5
Thickness
1
0.3
second (TWTT)
Contour lines
0,5 s
0,05 s
Erosion
Km
0
100
64°
63°
62°
61°
N
Santa Cruz
18°
Subandean belt
20°
Palaeovalleys
Erosion
Km
0
100

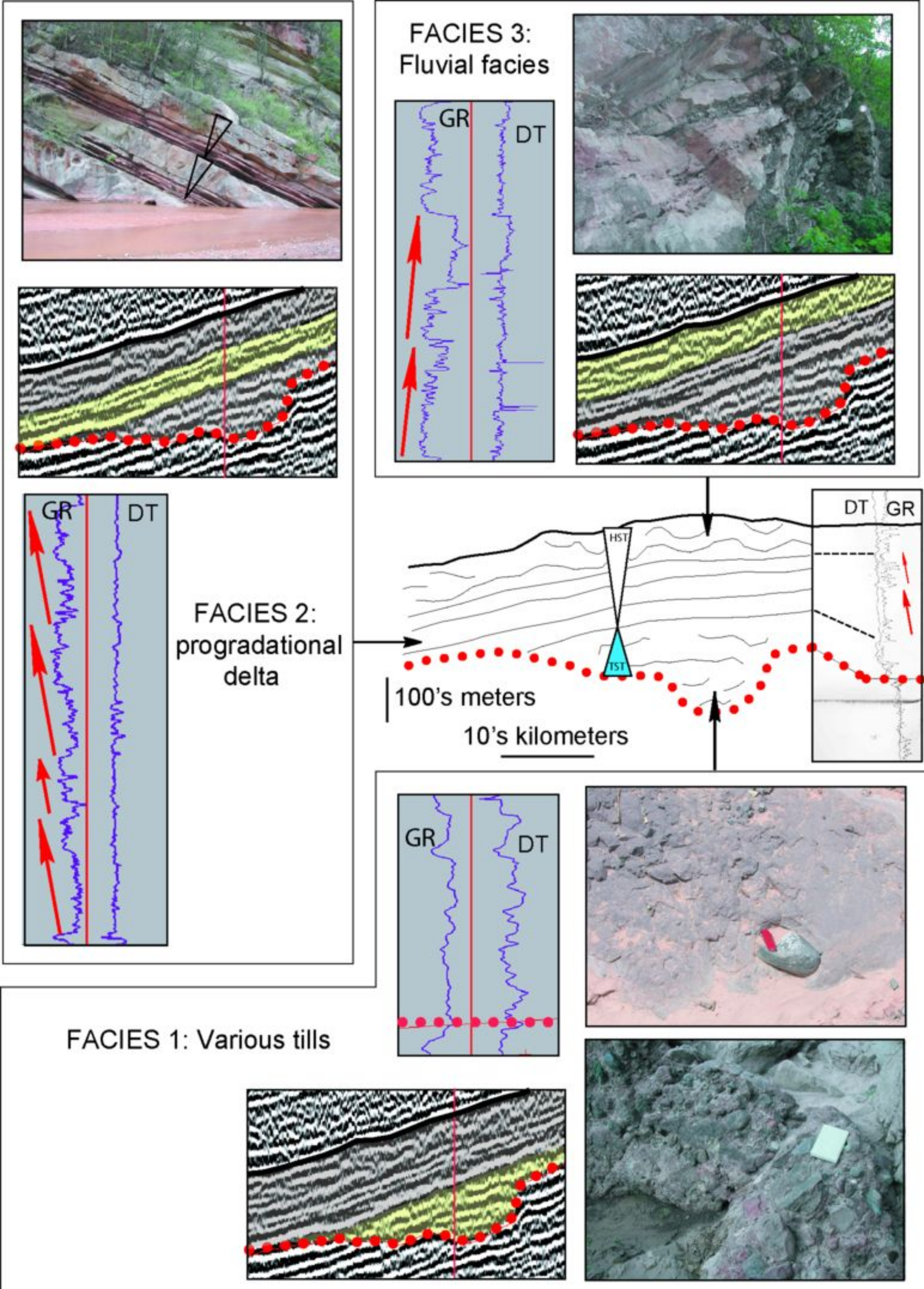

SW
NE
10 km
TC
600 m
BC
A
NW
SE
30 km
TC
600 m
B
64°
63°
62°
61°
N
Santa Cruz
18°
A
C
D
F
B
E
Subandean belt
G
20°
Paleovalleys
Erosion
Km
0
100
S
N
10 km
TC
700 m
BC
C
S
N
TC
700 m
10 km
BC
D
S
N
TC
700 m
10 km
BC
E
W
E
10 km
TC
500 m
BC
F
S
N
10 km
TC
700 m
BC
G

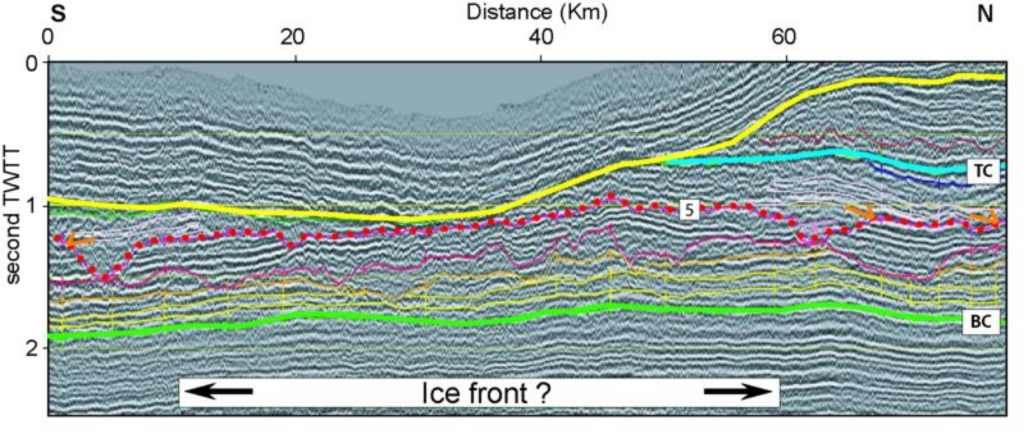


64°
63°
62°
61°
N
Santa Cruz
18°
20°
Subandean belt
Km
0
100
Surface 5
Surface 4

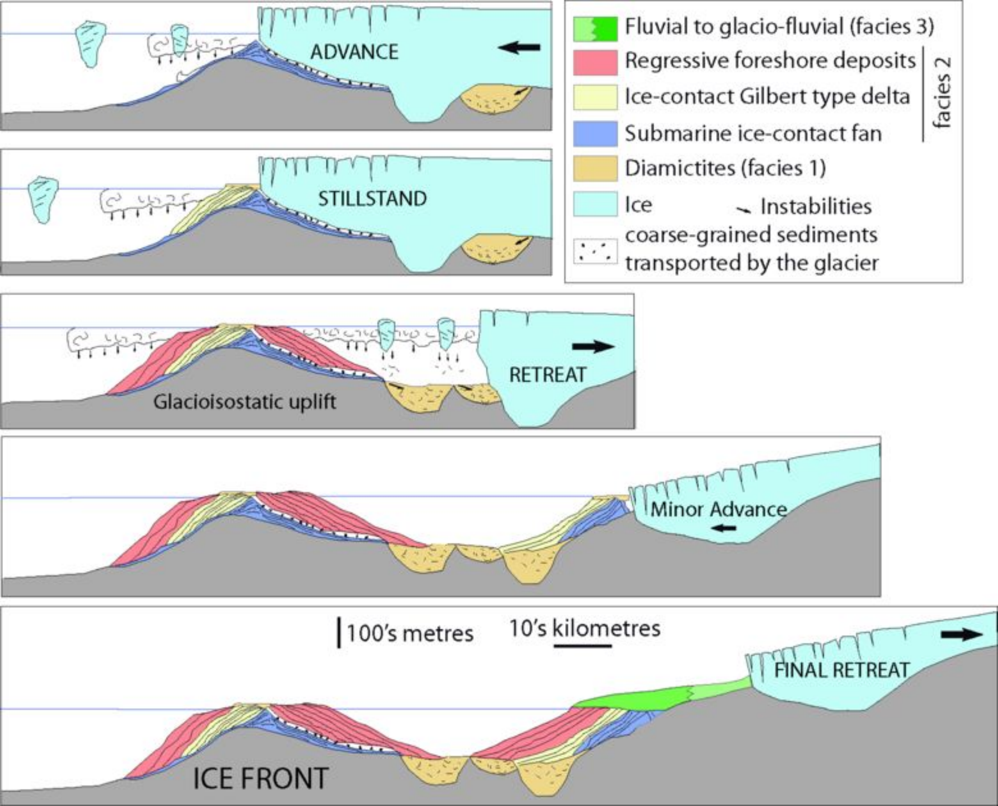


Palaeozoic/Mesozoic unconformity
Top of the Carboniferous
Base of the Carboniferous
Surface 5
downlaps
W
N
S
E
10 Km
0.5 s TWTT
e
e'
d
d'
c
c'
b
b'
a
a'
63°
62°
61°
18°
20°
N
Km
0
100


FACIES 3:
Fluvial facies
GR
DT
FACIES 2:
progradational
delta
HST
TST
100's meters
10's kilometers
DT
GR
FACIES 1: Various tills



S
Distance (Km)
N
0
20
40
60
0
1
2
second TWTT
5
TC
BC
Ice front ?



Fluvial to glacio-fluvial (facies 3)
Regressive foreshore deposits
Ice-contact Gilbert type delta
Submarine ice-contact fan
facies 2
Diamictites (facies 1)
Ice
Instabilities
coarse-grained sediments transported by the glacier
ADVANCE
STILLSTAND
RETREAT
Glacioisostatic uplift
Minor Advance
100's metres
10's kilometres
FINAL RETREAT
ICE FRONT

Type of incision	Process of incision	Sections	Width	Depth	Length	Basement	Sinuosity	Drainage patterns
Tunnel Valleys	hydraulic	U-shaped	M.= 1km <4 km	M. 250m <500 m	10' of km	rocks & sediments	low	anastomosing to tributary branching
Cross shelf trough*	abrasion	U-shaped	10-100' of km	M. 250m	100' of km	sediments	straight to very low	cross-cutting (no mix)
Fjord	hydraulic + abrasion	U-, V-shaped	1-20 km	< 3km	10' of km	rocks	straight (inherited)	branching to eratic
Chaco incisions	hydraulic + abrasion	U-, V-shaped	M.= 7.3km 3-21 km	500-700 m	>100 km	sediments	straight to very low	one anastomosed network (cross-cut?)